

Final Technical Report
For NASA Grant NAG-5-2483
"ASCA PV Phase Data Analysis and FRFREAD Maintenance"

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This report describes the activities at Penn State University supported by NASA Grant NAG-5-2483, "ASCA PV Phase Data Analysis and FRFREAD Maintenance". Initiated at Penn State in February, 1994, the aim of this investigation was to support analysis of data collected during the Japanese-U.S. ASCA (Advanced Satellite for Cosmology and Astrophysics) satellite mission Performance and Verification (PV) phase. After the initial turn-on of the satellite, experiments during the first six months of satellite operations were reserved for the use of the ASCA science team. During this time the behavior of the instruments was characterized by a set of observations chosen collectively by the team.

Dr. John Nousek of Penn State was named a member of the ASCA team by Prof. Yasuo Tanaka, in recognition of the efforts made in developing the FRFREAD software at Penn State, and for active participation in the ASCA team meetings in the U.S. and Japan during the mission development. Dr. Nousek served as U.S. coordinator for stellar targets during the PV target selection process. In this role he collected target proposals from the entire U.S. portion of the ASCA team which applied to normal stars (as opposed to X-ray binaries and compact objects), conducted an internal peer review, compared results with the Japanese stellar coordinator (Prof. K. Koyama of Kyoto University), and presented the proposed list to a meeting of the entire ASCA science team at ISAS, Japan.

In addition to Dr. Nousek, Dr. Robin Corbet and Prof. Gordon Garmire were also named team members. (Dr. Corbet subsequently resigned his position at Penn State to become head of the SOF for the Rossi X-ray Timing Explorer (RXTE) at Goddard, but continued to collaborate scientifically on the ASCA project.) Assisting these leaders were Dr. Kim Weaver and Dr. George Chartas, Research Associates at Penn State; and Mr. Chris Baluta, Mr. Brian Thomas and Ms. Kaori Nishikida, grad students at Penn State. (Dr. Weaver resigned her position at Penn State in early 1994, and was replaced by Dr. Chartas, but both continued to collaborate on ASCA work.)

In addition to facilitating the ASCA data analysis for five faculty and three grad students, supporting the work of the ASCA science working group, and providing material for many papers, these funds also were used to support continuing advice and maintenance to the FRFREAD software package. FRFREAD is used at the ASCA Data Facility at Goddard Space Flight Center to process all ASCA data (both U.S. and Japanese). It converts the raw data tapes (called FRF for First Reduction Files) into user accessible FITS format files, which are distributed to users by the ADF.

Observations of eight ASCA targets during the PV phase were lead by Penn State investigators supported by this grant. Dr. Nousek lead observations of the M dwarf flare star, AD Leo; the dwarf nova, SS Cyg; and the Seyfert galaxy, MCG -2-58-22. Dr. Corbet lead observations of the

X-ray binaries 1E1145.1-6141 and EXO 0748-676. Dr. Garmire lead observations of the Pleiades star cluster, the supernova remnant RCW86 and the bright M band diffuse X-ray background enhancement in the southern Galactic center region.

Observations of all of these sources were successfully executed, and the Penn State staff contributed or lead the analysis of the data resulting in the following papers based on ASCA PV analysis support:

1. Cappi, M., Mihara, T., Matsuoka, M., Hayashida, K., Weaver, K. and Otani, C. ApJ 458 149 (1996) "Warm Absorber, Reflection and Fe K Line in the X-ray Spectrum of IC 4329A"

Results from the X-ray spectral analysis of the ASCA (Astro-D) performance verification phase observation of the Seyfert 1 galaxy IC 4329A are presented. We find that the 0.4-10 keV spectrum of IC 4329A is best described by the sum of a steep ($\Gamma \sim 1.98$) power-law spectrum passing through a warm absorber plus a strong reflection component and associated Fe K line, confirming recent results (Madjeski et al. 1995; Mushotzky et al 1995). Further cold absorption in excess of the Galactic value and covering the entire source is also required by the data, consistent with the edge-on galactic disk and previous X-ray measurements.

2. Corbet, R., Asai, K., Dotani, T., and Nagase, F. ApJ 436, L15-L18 (1994) "Is the changing orbital period of EXO 0748-676 evidence for a triple system?"

We present eclipse timing measurements of the low-mass X-ray binary (LMXB) EXO 0748-676 made with ASCA. These measurements, when combined with previous results, are consistent with the hypothesis that eclipse times are modulated by a third body. The parameters of the orbit of the postulated third body are now apparently well constrained and will allow further observations to effectively test the hypothesis that EXO 0748-676 is a triple system. The derived orbital parameters are such that, unless the inclination angle is very low, a third body in the system must have a mass less than the lower limit for a main-sequence star.

3. Corbet, R., Smale, A., Ozaki, M., Koyama, K., and Iwasawa, K. ApJ 443, 786-794 (1995) "The spectrum and pulses of 1E 2259+586 from ASCA and BBXRT observations".

The 7 s X-ray pulsator 1E 2259+586 was observed for approximately 1 day in 1993 with the Advanced Satellite for Cosmology and Astrophysics (ASCA). Observations were also obtained with Broad Band X-ray Telescope (BBXRT) in 1990 a few months after Ginga had observed 1E 2259+586 to be brighter than normal and the BBXRT data show 1E 2259+586 to be at an intermediate brightness level. By contrast, the ASCA data appear to have been obtained during a more common lower luminosity state. The pulse profiles we obtain are consistent with a connection between flux and pulse shape reported from Ginga data, and the pulsator continues to spin down. We use our high spectral resolution data to search for cyclotron lines in the spectrum that were claimed from observations made with other satellites. We find that the ASCA spectra of 1E 2259+586 cannot be satisfactorily fitted with either a single power law or a combination of two power laws, and that significant residuals occur around 1.5 and 5 keV. However, a combination of a power

law and blackbody gives a good fit over the entire ASCA energy band with no evidence of spectral features. We have reanalyzed a Ginga LAC spectrum and find that this is also significantly better fitted by this two-component spectrum than a single power law.

4. Day, C., Zylstra, G., White, N., Nagase, F. Corbet, R. and Petre, R. BAAS 186, #48.02 (1995) "ASCA Observations of GRO J1008-57 & EXO 2030+375"

ASCA observations of two X-ray transient pulsars, GRO J1008-57 and EXO 2030+375, are presented. Both sources were observed close to the end of an outburst, though not in quiescence. Pulse phase spectroscopy reveals, in both sources, that the spectrum flattens at the interpulse. This finding is consistent with the idea that the pulsar beam is pencil-shaped and that the interpulse corresponds to viewing the polar cap along the magnetic field lines.

5. Mukai, K., Gotthelf, E., Soong, Y., Ishida, M., Osborne, J. and Garmire, G. BAAS 184, #45.02 (1994) "ASCA Observation of AM Her".

AM Herculis, the prototypical magnetic cataclysmic variable, was observed with ASCA on 27 Sep 1993 for approximately 1 day. We present light curves in several different energy bands folded on the orbital period, showing that AM Her was in the normal mode with one pronounced X-ray minimum per orbital period. We also find that light curves differ at different energies, particularly around the orbital minimum. A spectrum extracted for the minimum is significantly softer than one for orbital maximum. We discuss possible causes of this phenomenon. We will also show the complex structures of the spectrum in the Fe K line region and discuss what we can learn from the lines regarding the geometry and physics of the X-ray emitting region.

6. Nousek, J., Baluta, C., Corbet, R., Mukai, K., Osborne, J. and Ishida, M. ApJ 436, L19-L22 (1994) "ASCA observations of SS Cygni during an anomalous outburst"

SS Cygni was observed by the ASCA satellite on 1993 May 27, the first cataclysmic variable studied by ASCA. The observations were conducted while the system was in an outburst of the 'anomalous' variety. The SIS spectrum cannot be explained by two-temperature Raymond-Smith coronal plasma models as invoked in previous studies with lower spectral resolution. Significantly better agreement is found for models with plasma emission at $kT = 0.8, 3.5$ keV and thermal bremsstrahlung at $kT = 18$ keV. The gas imaging spectrometer (GIS) data are consistent with the solid state imaging spectrometer (SIS) data, showing evidence for Fe line emission but showing no evidence of pulsation over times ranging from seconds to minutes. These observations seem at variance with standard theory in two regards: we simultaneously see hard X-rays and optically thin soft X-rays while the system is in outburst, and we see a nonsmooth emission measure distribution. We speculate on possible scenarios which might resolve these differences.

7. Nousek, J., Baluta, C., Mukai, K., Osborne, J. and Ishida, M. BAAS 185, #45.01 (1994) "ASCA Observations of SS Cyg"

SS Cygni was observed by the ASCA satellite on 27 May 1993, the first cataclysmic variable studied by ASCA. We interpret this result as evidence for a paucity of material emitting in

the range near 5 keV. Such a deficit of intermediate temperature emission measure can be well reconciled with boundary layer models of the type presented by Narayan & Popham. In such models the emission we see below 2 keV originates in the optically thick inner edge of the accretion disk, while the hard component comes in a narrow spike at the inner edge of the boundary layer. The optically thin part of the accretion disk provides little emission measure, which explains the deficit of 5 keV emitting material.

8. Nousek, J. and Nishikida, K. X-ray Imaging and Spectroscopy of Cosmic Hot Plasmas: Proceedings of the International Conference on X-ray Astronomy, in press (1996) "ASCA Observations of a Flare Star in Quiescence: AD Leo"

AD Leo, a single dM4e flare star, is a popular target for activity studies because of its frequent flares. ASCA observed AD Leo for a full day on 24 May 1993, in hopes of detecting a flare, supported by simultaneous ground observations. Although no optical flare and no X-ray variation by more than a factor of two was seen during 24,000 seconds of observing, the ASCA data allow us to make the best available X-ray spectra of a flare star.

9. Thomas, B., Corbet, R., Smale, A. and Asai, K. BAAS 186, #48.06 (1995) "A multi-mission investigation of EXO 0748-676: evidence for complex secular changes in the accretion structure of this system".

We present data from two ASCA observations (1993 March 17.92-18.12 and 1993 May 7.24-8.09) of the high inclination ($i \sim 80^\circ$), dipping, eclipsing Low-mass X-ray Binary EXO0748-676. We have examined the intensity selected dipping and quiescent (non-dipping, non-eclipsing, non-bursting) behavior of EXO0748-676 in these observations.

10. Weaver, K., Nousek, J., Yaqoob, T., Hayashida, K. and Murakami, S. ApJ 451, 147 (1995) "An ASCA X-Ray Spectrum of a Prototype Bare Seyfert 1 Nucleus in MCG -2-58-22"

We present new X-ray spectral data for the Seyfert 1 galaxy MCG -2-58-22 obtained with the Advanced Satellite for Cosmology and Astrophysics (ASCA). The simplicity of the spectrum between 0.5 and 6 keV due to a lack of complex absorption or an appreciable contribution from Compton reflection allows a measurement of the true continuum slope. Accounting for the excess flux at ~ 1.0 keV, the intrinsic photon index is $\Gamma = 1.75 \pm 0.05$. This is flatter than $\Gamma \sim 2.0$ predicted by current pair/reflection models and thermal Comptonizations models, although no conclusions can be drawn until the distribution of intrinsic indices for Seyfert galaxies is known.

11. Weaver, K., Nousek, J., Yaqoob, T., Mushotzky, R., Makino, F. and Otani, C. ApJ 458, 169 (1996) "X-Ray Reprocessing by a Molecular Torus in the Seyfert 1.9 Galaxy NGC 2992"

We present new X-ray spectral data for the Seyfert 1.9 galaxy NGC 2992 obtained with the Advanced Satellite for Cosmology and Astrophysics (ASCA). These data are combined with archival and published data to outline a 16 year history of flux variability in the X-ray band. We find that, while the 2-10 keV flux has decreased by a factor of ~ 20 in 16 years, the flux of the Fe K α fluorescence line has decreased by only a factor of 2-3, and the inferred

amount of Compton reflection is 5 times stronger compared to the continuum than 16 years ago.

12. Weaver, K., Yaqoob, T., Holt, S., Mushotzky, R., Matsuoka, M. and Yamauchi, M. ApJ 436, L27 (1994) "New X-ray spectral observations of NGC 4151 with ASCA"

We present new X-ray spectral data for the well-studied Seyfert galaxy NGC 4151, which was observed twice for about 20 ks each during the ASCA performance verification phase, once on 1993 May 25 and again on 1993 November 5. The source underwent complex spectral variability, and the observed 2-10 keV flux increased by a factor of 2 while the intrinsic 2-10 keV flux increased by no more than 20%. The data can be modeled with either a dual cold absorber plus a soft X-ray excess consisting of scattered continuum flux and an additional 'ultrasoft' X-ray excess component, or a warm absorber plus scattered continuum flux. There is evidence for variability at less than 1 keV energies that is unrelated to the 2-10 keV continuum. For an ionized-absorber description of NGC 4151, changes in the ionization state of the absorber appear to be unrelated to changes in the ionizing continuum.

13. Weaver, K., Yaqoob, T., Holt, S., and the Asuka Team BAAS 184, #59.10 (1994) "New X-ray Spectral Data of NGC 4151 observed with Asuka"

We present new X-ray spectral data for the well-studied Seyfert 1 galaxy NGC 4151. This source was observed for 20 ksecs twice during the Asuka PV phase, once on 25 May 1993 and again on 5 November 1993. NGC 4151 underwent strong flux and spectral variability between the two observations; its flux increased by a factor of three while there was an apparent column density decrease from 8 to $3 \times 10^{22} \text{ cm}^{-2}$. At energies of less than 1 keV, the data from the Asuka Solid-state Imaging Spectrometer (SIS) have a much higher S/N than the spectra that were obtained with the Broad Band X-Ray Telescope (BBXRT). We find that the known soft X-ray excess in NGC 4151 is more complicated than previously thought. In addition to the scattered (a.k.a. "partial covering") soft excess component, we have detected an "ultrasoft" soft excess component that can be described by a 0.2 keV thermal bremsstrahlung spectrum. There is also evidence for line emission between 0.6 and 0.9 keV. We will discuss how the ultrasoft excess may relate to the extended soft X-ray emission seen by the Einstein Observatory HRI and the Rosat HRI.

14. Weaver, K., Nousek, J., and Yaqoob, T. BAAS 185, #108.03 (1994) "ASCA Observations of Fe K α Line Profiles in Seyfert Galaxies"

We present new X-ray spectral data for Fe K α lines in five Seyfert galaxies observed recently with the ASCA satellite. NGC 4151, MCG-2-58-22, and IC 4329A were observed during the performance verification phase of the mission; NGC 2992 and MCG-5-23-16 were observed during the AO-1 guest observer phase. We find that all of the Fe K α line energies are consistent with fluorescence of neutral or weakly ionized Fe. The other Fe K α line properties such as intrinsic line width and equivalent width (EW) have a range of values, suggesting that there is not a ubiquitous origin for Fe K α lines in Seyfert galaxies.

15. Yaqoob, T., Serlemitsos, P., Mushotzky, R., Ricker, G., Woo, J., Weaver, K., Kii, T.,

Mitsuda, K., Kotani, T. and Hayashida, K. PASJ 46, L49-L53 (1994) "The X-ray emission of 3C 273 observed with ASCA".

We report preliminary results of an Advanced Satellite for Cosmology and Astrophysics (ASCA) observation of 3C 273. There is no spectral variability within the ASCA observation, in contrast to the longer term behavior found with European X-ray Observatory Satellite (EXOSAT) and Ginga which established significant changes in the spectral index of the power-law continuum on timescales of a week or more, uncorrelated with luminosity. Comparison of the ASCA data with a simultaneous Roentgen Satellite (ROSAT) Ginga observation in 1990 December shows that while the shape of the spectrum above approximately 1 keV is essentially the same, the flux in the soft component, below approximately 1 keV, is considerably weaker relative to the hard component in the ASCA observation.

16. Yaqoob, T., Edelson, R., Weaver, K., Warwick, R., Mushotzky, R., Serlemitsos, P. and Holt, S. BAAS 187, #50.13 (1995) "The Iron K Line Profile in NGC 4151 and the Evidence for a Relativistic Accretion Disk"

We present the first measurements of the Fe K α line profile in NGC 4151 from ASCA observations performed in May, November and December 1993. The apparent line profile is asymmetric, consisting of a peak at $\sim 6.3 - 6.4$ keV, a sharp drop on the blue side below ~ 7 keV and a broad red wing extending to $\sim 4-5$ keV. This first clear indication of complex structure confirms earlier tentative measurements of the Fe-K region with BBXRT. The line intensity, equivalent width and detailed shape are model-dependent. Interpretation of the profile in terms of emission from a disk rotating around a central black hole strongly constrains the putative disk to be face-on, the inferred inclination angle being 0_{-0}^{+19} degrees.

17. Yaqoob, T., Edelson, R., Weaver, K., Warwick, R., Mushotzky, R., Serlemitsos, P. and Holt, S. ApJ 453, L81 (1995) "The Iron K Line Profile in NGC 4151"

We present the first measurements of the Fe K α line profile in NGC 4151 from ASCA observations performed in May, November and December 1993. The apparent line profile is asymmetric, consisting of a peak at $\sim 6.3 - 6.4$ keV, a sharp drop on the blue side below ~ 7 keV and a broad red wing extending to $\sim 4-5$ keV. This first clear indication of complex structure confirms earlier tentative measurements of the Fe-K region with BBXRT. Interpretation of the profile in terms of emission from a disk rotating around a central black hole strongly constrains the putative disk to be face on, but this contradicts the current body of knowledge of the geometry of this source. If the apparent red wing is not in fact part of a peculiar continuum, then a face-on disk may be allowed only if the collimated structure observed at the parsec scale is misaligned with respect to the disk normal by at least 20 deg and iron is overabundant by a factor of ~ 2 , with some additional caveats. Alternatively, a different geometry of line-emitting material may be required. In contrast to clear variability in the soft X-ray line emission below ~ 1 keV between the observations, these data show no significant variability of the Fe K alpha overall line shape, intensity, or equivalent width.

In addition to these nine papers published in refereed journals and eight unrefereed conference proceedings or meeting abstracts, one Ph.D. thesis (Mr. Brian Thomas) and M.S. thesis (Mr.

Chris Baluta), and two graduate research papers (Mr. Baluta and Ms. Kaori Nishikida) were prepared based on ASCA PV phase data. Mr. Thomas is currently employed at the Goddard Space Flight Center and expects to complete his thesis this semester. Mr. Baluta has completed his M.S. degree and is employed at the AXAF Science Center at MIT. Ms. Nishikida is currently enrolled as a PSU grad student.